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# Exploring Engineered Complex Adaptive Systems of Systems

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**Abstract**

The rise of automation in many systems; and technology ubiquity in general, present some complex operational environments that require highly collaborative Complex Adaptive Systems of Systems (CASoS) solutions. This paper describes the need to engineer CASoS and explores how they may be applied to address complex problems. This effort builds on a developing body of knowledge in complex systems and focuses on understanding characteristics and measures of CASoS with an ultimate goal on developing engineered CASoS. The implications of deeper CASoS understanding hold potential for more effective future responses to naturally-occurring and adversarial CASoS. Thus, there stands much to gain in increasing this body of knowledge.


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## 1. Introduction

Engineered (man-made) systems become necessarily complex when they must perform effectively and function in response to highly uncertain (complex) environments.[5] Planning all the possible functions of such systems becomes very challenging when all of the possibilities that may be encountered cannot be predicted. When engineered systems become complex they start outgrowing the bounds of traditional (or classical) system

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engineering (TSE) methods. Traditional systems are expected to perform foreseeable tasks in a bounded environment, whereas complex systems are expected to function in complex, open environments with unforeseeable contingencies. Complex Systems Engineering (CSE) does not "…primarily seek to produce predictable, stable behavior within carefully constrained situations, but rather to obtain systems capable of adaptation, change, and novelty—even surprise!"[5]

Advances are being made in the science of complexity based on insights gained from studying complexity found in natural and social systems.[2] These are leading to novel approaches to designing and developing complex man-made systems.[3] A central tenet of complex systems is the principle of emergence: that the whole is greater than the sum of its parts. This implies potential advantages for higher-level functionality emerging from engineered elements comprising a system. It also implies emergent system behavior that is unpredictable. In other words, when the principle of emergence is applied to complex engineered systems, these man-made systems may behave in unexpected ways.[4] The newly forming field of CSE is attempting to address this question and explore methods to best engineer complex systems to take advantage of their complexity while also managing the unpredictability and large scope of such systems.[5]

The rise of automation in many systems; and technology ubiquity in general, present some complex operational environments that require highly collaborative system of systems (SoS) solutions. One example is the potential military advantage gained from managing distributed warfare assets as a SoS to address demanding tactical threats. A future challenge may be the management of complex airspaces with a mix of manned and unmanned commercial and civilian aircraft and drones. Another operational need in the future may be an automated land transportation system of self-driving cars and smart traffic management, intersections, and guidance. Such challenging operations will require a SoS that is agile and can be continually modified to meet the changing demands of the operational situation. This paper explores concepts for a mutable type of SoS that addresses these needs: the engineered CASoS.

## 2. CASoS Concepts

What makes a system complex? Experts in the field of complexity science have not agreed on an official definition of a complex system; but a number of definitions exist that contain similarities. Two definitions given in Melanie Mitchell's book on complexity capture different aspects of complex systems.[6] The first definition captures the large size, collaborative behavior, and lack of central control: "…a system in which large networks of components with no central control and simple rules of operation give rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution." The second definition focuses on emergence and self-organization: "…a system that exhibits nontrivial emergent and self-organizing behaviors."[6] Self-organization refers to the ability of the components of a complex system to create organized behavior without an internal or external controller. Will Allen distinguishes between complex and complicated systems by their outcomes: for complicated systems "there can be a relatively high degree of certainty of outcome repetition"; while for complex systems, "uncertainty of the outcome remains."[7] The implications are that "we cannot build a CAS from scratch and expect it to turn out exactly in the way we intended."[7]

Sandia's Phoenix initiative is studying CASoS.[8] They define CASoS as "vastly complex eco-socio-economical-technical systems which we must understand to design a secure future for the nation and the world.[9] The Phoenix initiative defines CASoS in terms of the definitions of the component terms. "Complex refers to complex behavior, encompassing behavior that is greater than a sum of the parts, exceeds expectations, difficult to understand, emergent, results from interactions of components. Adaptive refers to the ability of the system to change itself in response to external stimuli. SoS refers to the structure of the system, being made of parts that are themselves systems."[2] Further, they developed the idea of "aspirations"—or engineering goals that can be used to influence CASoS to "solve problems, exploit opportunities, and/or achieve goals."[9] They clearly define aspiration categories: "*predict*; *prevent* or *cause*; *prepare*; *monitor*; *recover* or *change*; and most encompassing, *control*."[9] Additionally, they define three key components that must accompany an aspiration: "*decision*, *robustness of decision*, and *enabling resilience*."[9]

A Venn diagram of SoS, shown in Figure 1, illustrates possible subcategories and provides a context for CASoS.